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Another intermediate mass black hole in a starburst galaxy?: The luminous X-ray source in NGC 3628 reappears

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ABSTRACT

In a 52 ks-long *Chandra* ACIS-S observation of the nearby starburst galaxy NGC 3628, obtained to study the starburst-driven outflow from this galaxy, we have detected a very luminous ($L_{\rm X} \approx 1.1 \times 10^{40}\,{\rm erg\,s^{-1}}$ in the 0.3 − 8.0 keV energy band) point source located at least 20″ (~ 970 pc) from the nucleus of the galaxy. No radio, optical or near-IR counterpart to this source has been found.

This is most probably the reappearance of the strongly-variable X-ray-luminous source discovered by Dahlem, Heckman & Fabbiano (1995), which

faded by a factor $\gtrsim 27$ between December 1991 and March 1994 (at which point it had faded below the detection limit in a *ROSAT* HRI observation). This source is clearly a member of an enigmatic class of X-ray sources that are considerably more luminous than conventional X-ray binaries but less luminous than AGN, and which are not found at the dynamical center of the host galaxy.

The *Chandra* spectrum is best-fit by an absorbed power law model with a photon index of $\Gamma = 1.8 \pm 0.2$, similar to that seen in Galactic BH binary candidates in their hard state. Bremsstrahlung models or multi-color disk models (the favored spectral model for objects in this class based on *ASCA* observations) can provide statistically acceptable fits only if the data at energies $E > 5$ keV is ignored. This is one of the first X-ray spectra of such an object that is unambiguously that of the source alone, free from the spectral contamination by X-ray emission from the rest of the galaxy that affects previous spectral studies of these objects using *ASCA*.

Subject headings: black hole physics — galaxies: individual (NGC 3628) — galaxies: starburst — X-rays

1. Introduction

It has become apparent that there exists a class of extragalactic X-ray sources significantly more luminous than normal X-ray binaries or supernova remnants, but less X-ray luminous than conventional AGN such as Seyfert nuclei (Fabbiano 1989). These intermediate-luminosity X-ray objects (IXOs, Ptak 2001) or ultraluminous X-ray sources (ULXs, Makishima et al. (2000)) have X-ray luminosities in the range $10^{39} - 10^{41}\,\mathrm{erg\,s^{-1}}$ (equivalent to the entire Eddington luminosity for accretion onto a $7 - 700 M_{\odot}$ mass object), but are generally *not* found at the dynamical center of the galaxy (Colbert & Mushotzky (1999); Roberts & Warwick (2000)), and hence are not likely to be supermassive black holes (SMBHs) radiating inefficiently.

For example, recent *Chandra* High Resolution Camera (HRC) observations of the prototypical starbursting dwarf peculiar galaxy M82 (Kaaret et al. (2001); Matsumoto et al. (2001)) conclusively show that the bright X-ray variable source (peak luminosity $L_{\mathrm{X}} \sim 9 \times 10^{40}\,\mathrm{erg\,s^{-1}}$ in the 0.5–10.0 keV energy band) previously seen in *Einstein*, *ROSAT*

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& *ASCA* observations (see Watson, Stanger & Griffiths (1984); Bregman, Schulman & Tomisaka (1995) and Ptak & Griffiths (1999) among many other papers too numerous to mention) lies $9''$ ($\sim 160\,\mathrm{pc}$) away from the dynamical center of the galaxy.

The nature and origin of these objects remains unknown. The variability argues against models of supernova remnants evolving in dense surroundings (Franco et al. 1993), where a monotonic decline in X-ray luminosity might naively be expected (but note this is not necessarily always true (Cid Fernandes et al. 1996)). The possible association between the luminous X-ray source in M82 and the known young supernova remnant 41.95+57.5 (Stevens, Strickland & Wills 1999), advanced based on the source position derived from *ROSAT* HRI data, appears incorrect based on the more accurate *Chandra* astrometry. No persistent counterpart to this source at other wavelengths has been confirmed, although the transient radio source 41.4+59.7 (Kronberg & Sramek 1985), seen in one observation in 1981 but not subsequently, lies within the positional error circle of the M82 IXO[2] (Kaaret et al. 2001) and may be associated with the IXO.

The currently favored interpretation is that these might be black holes of mass $10^2 \lesssim M_{\rm BH}(M_\odot) \lesssim 10^4$, intermediate between the SMBHs ($M_{\rm BH} \sim 10^6 - 10^9\,M_\odot$) found in traditional AGN such as Seyfert galaxies (formed in some as yet unknown manner, which is possibly related to the growth of stellar bulges (Gebhardt et al. (2000); Ferrarese & Merritt (2000))) and black holes of a few solar masses (formed naturally as a consequence of the stellar evolution of the most massive stars (Brown, Weingartner & Wijers 1996)). However, alternative explanations not involving intermediate mass black holes do exist. King et al. (2001) argue that these X-ray sources are conventional high-mass X-ray binaries in which the X-ray emission happens to be beamed in our direction. Roberts et al. (2001) report a possible optical blue continuum counterpart to an IXO in NGC 5204, which might be an extremely luminous O star or a cluster of young stars.

Here we report on the re-detection of a strongly variable X-ray luminous point source (peak $L_{\rm X} \sim 5\times10^{40}\,\mathrm{erg\,s^{-1}}$) located at least 900 pc from the nucleus of the nearby starburst galaxy NGC 3628 (D = 10 Mpc, Soifer et al. (1987)). This source, discovered to be variable by Dahlem et al. (1995), had faded by a factor $\gtrsim 27$ between two *ROSAT* HRI observations taken in late 1991 and early 1994 (when it was too faint to be detected). This source is the brightest X-ray source in a recent 52 ks-long Chandra ACIS-S observation we obtained of NGC 3628.

With the arcsecond spatial resolution of *Chandra* we have been able to measure the

[2]We adopt the purely descriptive term IXO to refer to these objects over the alternative ULX as it makes no assumptions about their nature.

absolute position of this source to an accuracy of $0\farcs5$, and obtain one of the first unambiguous X-ray spectra of an IXO[3], free from contamination by unrelated X-ray emission from the rest of the galaxy.

2. Data analysis and reduction

NGC 3628 was observed with the *Chandra* ACIS-S instrument on 2000 December 2, for a total exposure time (after the removal of background flares) of 52289 s. The nucleus of the galaxy was placed at the aim point of the back-illuminated S3 chip (the back illuminated chips are more sensitive to soft X-ray emission, and do not suffer from the radiation damage that compromises the spectral resolution of the front illuminated ACIS chips). Much, but not all, of the disk of NGC 3628 falls within the boundaries of the S3 chip.

The data was reduced and analyzed using CIAO (version 1.1.5), HEASOFT (version 5.0.2) and XSPEC (version 11.0.1). The latest *Chandra* calibration and spectral response files appropriate for this observation were used. Spectra were binned to achieve at least 20 counts per channel, to allow the use of χ^2-fitting. Our reduction and processing followed the guide lines released by the *Chandra* X-ray Observatory Center (CXC) and the ACIS instrument team[4].

The data reduction and analysis will be described in more detail in a forthcoming paper on the diffuse X-ray emission from this galaxy's starburst-driven superwind (Strickland et al. 2001, in preparation). Here we will focus only on the brightest point source within the disk of the galaxy.

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[3]At the initial time of writing no other *Chandra* spectra of any IXO, including the M82 source, had been published. This is most likely because "pile-up" (see § 4) in the CCD detectors becomes a problem for point sources slightly brighter than the bright source in NGC 3628. For sources as bright as the one in M82, it can be so severe as to prevent any meaningful spectral analysis. A paper by Roberts et al. (2001) appeared while this paper was undergoing the referee process which very briefly discusses the *Chandra* ACIS spectrum of an IXO in NGC 5204.

[4]The CIAO (v1.1.5) Science Threads can be found at http://asc.harvard.edu/ciao1.1/threads/threads.html, the ACIS instrument team's recipes at http://www.astro.psu.edu/xray/acis/recipes/.

3. Source location

The *Chandra* observation of NGC 3628 reveals a large number of hard X-ray point sources, embedded in highly structured and wide-spread diffuse soft X-ray emission (see Fig. 1, which only shows the central $2'$ region around the nucleus of the galaxy). One particularly luminous point source, at a position of $\alpha = 11^h20^m15\overset{s}{.}75$, $\delta = +13^\circ35'13\overset{''}{.}6$ (J2000.0), stands out above all the rest, and accounts for a large fraction of the hard X-ray emission from the galaxy (see § 4). Following the recommended naming convention for *Chandra* sources, we name this source CXOU J112015.8+133514, but for convenience we shall refer to it for the remainder of this paper as the IXO.

Previous X-ray studies of NGC 3628 had assumed that the X-ray emission was centered on the nucleus of the galaxy, given the limited absolute positional accuracies of previous X-ray instruments (the highest resolution observations prior to *Chandra* were with the *ROSAT* HRI, which had 1σ absolute positional uncertainties of $\sim 6''$). In contrast, source coordinates derived from this *Chandra* observation are accurate to $0\overset{''}{.}5$, based on a cross-correlation between the positions of X-ray sources in the S2 and S3 chips (excluding X-ray sources within the disk of NGC 3628) and optical sources from the APM catalog (Maddox et al. 1990).

With these more accurate source coordinates it is clear that the IXO is *not* at the nucleus of NGC 3628, if we make the reasonable assumption that the peaks of the K-band, HI, CO and radio recombination line emission correspond to the nucleus of the galaxy (See Table 1 for references. All of these emission maxima are within $3''$ of each other). The nucleus of NGC 3628 is approximately $20''$ to the east of the IXO (see Table 1). An offset of $20''$ corresponds to a projected distance of 970 pc (possibly considerably more physically), given the assumed distance of 10 Mpc. Although the kinematic center of the larger-scale HI distribution (Wilding, Alexander & Green 1993) is offset to the north-west of the nucleus by about $12''$, it is also $\sim 20''$ from the IXO.

As this source has a luminosity only a factor ~ 4 lower than the peak luminosity of the bright source seen by the *ROSAT* HRI (see § 5), and there were no other comparable luminosity sources seen in previous observations, it seems most probable that the IXO is the same source as the variable HRI source discussed in Dahlem, Heckman & Fabbiano (1995). Comparison of the *ROSAT* HRI images with the 0.3 – 2.0 keV *Chandra* images supports this interpretation, based on the relative position of other weak X-ray sources found in both sets of observations.

We have searched for an optical, near-IR or radio counterpart to this source. R-band optical images (Fabbiano, Heckman & Keel 1990) reveal the location of the IXO to be

within one of the dust lanes obscuring much of the disk of NGC 3628. Within a $2''$ radius of the *Chandra*-derived position of the IXO the optical surface brightness is relatively uniform, and there are no obvious star clusters or other features visible. K-band imaging, taken by Colbert, also revealed no features within a $5''$ radius of the IXO's position. No radio source was detected in the 15 GHz VLA A-configuration data from Carral, Turner & Ho (1990). The 3σ upper limit of 0.24 mJ/beam corresponds to a radio power $P < 3 \times 10^{18}$ W Hz^{-1}, about an order of magnitude more luminous than the galactic supernova remnant Cas A, but $\sim 10 - 1000$ times lower than typical radio supernovae (Weiler et al. 1986).

4. Spectral properties and count rates

4.1. Spectral fitting

Fig. 2 shows the ACIS spectrum of the IXO, extracted using a circular aperture of radius $6''$. For the purposes of background subtraction we used a circular aperture of radius $30''$, offset $20''$ directly to the west of the IXO, having excluded the region around the bright source itself and around the five other *Chandra*-detected X-ray sources falling within this region. Use of a local background region is warranted, given the presence of extended diffuse soft X-ray emission (associated with the starburst-driven wind) throughout the disk of NGC 3628.

We fit a variety of different spectral models to the *Chandra* spectrum using the data in the energy range 0.3 – 8.0 keV, focusing mainly on models traditionally associated with AGN (absorbed power laws) or other IXOs observed with ASCA (multi-color disk models, see Makishima et al. (2000)).

An absorbed power law provides the simplest statistically acceptable fit to the spectrum (Fig. 2, table 2). Absorbed multi-color disk, bremsstrahlung or MEKAL hot plasma models (Mewe, Kaastra & Liedahl 1995) are all statistically unacceptable fits to the IXO spectrum (reduced $\chi^2 \sim 1.1 - 1.4$).

Statistically good fits can be obtained using these models if an additional hard component was added to the model. Two component spectra, comprising a soft multi-color disk with a hard power law tail, have been found for other IXOs using *ASCA* spectroscopy (Takano et al. (1994); Colbert & Mushotzky (1999)). The model parameters of the added power law or Gaussian line model used as this hard component are very poorly constrained, and physically some of the parameters are not realistic, so it is not clear if this apparent hard component is real or not.

A small fraction of the events detected from this source will be due to pile-up (the mis-identification of two or more X-ray photons falling within the same pixel during a single CCD exposure of 3.2s as a single photon of higher energy). This has many affects, the simplest of which is a systematic hardening of the spectrum, which is a possible cause of the additional hard component the spectral fits appear to require. The PIMMS count-rate calculator predicts $\sim 8\%$ of the total counts are piled-up given the observed count rate of this source. This is close to the 10% level at which the CXC warn that spectra are likely to be significantly affected, suggesting pile-up may be a problem.

To investigate whether there is appreciable pile-up in the NGC 3628 IXO spectrum we compared the event grade branching ratios (the fraction of events with a given grade, see the *Chandra* Proposers Observatory Guide) for photons with $2 \leq E$ (keV) ≤ 8 from the IXO (1646 events) with the summed emission from the 14 next brightest point sources seen in NGC 3628 which are individually too faint to suffer from any pile-up (672 events in total). Pile-up leads to a systematic increase in the fraction of events with high grades (e.g. ASCA grades 5, 6 & 7). However, we find that the event grade branching ratios for the IXO and the summed fainter point source emission are identical to within 2σ for all grades, which suggests that there is no appreciable pile-up in the NGC 3628 IXO spectrum. Applying this technique to the public 34 ks *Chandra* ACIS-I observation of M82 (ObsID 361) shows a very significant migration of the events from the M82 IXO to higher grades with respect to the fainter point sources in M82.

Other evidence that the hard excess seen in the NGC 3628 IXO is not due to pile-up is that spectral fitting of a brighter point source seen in our two *Chandra* observations of NGC 253 (Weaver et al. , in preparation) shows no sign of a hard excess, even though the predicted pile-up fraction is 12 – 14% (higher than the NGC 3628 IXO), and the total number of counts in the spectrum is similar to that in the NGC 3628 IXO spectrum.

Statistically acceptable multi-color disk spectral models *can* be obtained if we restrict the energy range used to 0.3 – 5.0 keV (*i.e.* deliberately excluding data in the energy range where the multi-color disk model does worst). However, it should be noted that absorbed power law and absorbed bremsstrahlung models provide marginally better fits to the data in this restricted energy range. It therefore seems that a power law model provides the best description of the current spectral state of this source, and that a multi-color disk model does *not* provide an adequate fit to the spectrum of the IXO.

Source count rates and absorption-corrected fluxes and luminosities, assuming the power law spectral model (using the restricted 0.3 – 5.0 keV energy range), are given in Table 3. All spectral fits give absorption columns in the range $N_{\rm H} = 5 - 8 \times 10^{21}\,{\rm cm}^{-2}$. These columns are consistent with foreground absorption of the source by the edge-on disk of NGC 3628,

and its location in or behind the optical dust lane.

4.2. Comparison to previous spectral studies of NGC 3628

It is not easy to compare our *Chandra* spectra of the IXO with previous X-ray spectral studies of the nucleus NGC 3628, using the *ROSAT* PSPC (Dahlem, Heckman & Fabbiano 1995) or *ASCA* (Yaqoob et al. 1995), given the significant variability of the IXO and the much poorer spatial resolution of the earlier observations (The *ROSAT* PSPC spectrum covers a region $2' = 5.8$ kpc in radius, and the *ASCA* spectra a region $3' = 8.7$ kpc in radius).

The most detailed existing spectral study is that of Dahlem, Weaver & Heckman (1998), who performed a joint spectral fit of the PSPC and *ASCA* spectra, taking into account the variability between the two observations. This joint spectrum is best characterized by two soft thermal components and a hard absorbed power law. The photon index and hydrogen column derived for the power law component ($\Gamma = 1.63^{+0.14}_{-0.17}$ and $N_{\rm H} = 9 \pm 2 \times 10^{21}\,{\rm cm}^{-2}$) agree well with the *Chandra*-based power law fit to the emission from the IXO.

The close agreement between the power law slopes may be fortuitous, as most of the hard X-ray counts in the ASCA spectrum must have been from other point sources in NGC 3628 and not from the IXO itself. Even in its present state, which is several times more luminous than it was during the 1993 ASCA observations (see § 5), hard X-ray emission from sources other than the IXO still provide a significant fraction ($\sim 33\%$) of the 2.0 – 8.0 keV count rate in the central region of NGC 3628. Within a $3'$ radius region, the *Chandra* observations reveal at least 33 other point-like X-ray sources, in addition to the diffuse thermal emission associated with the starburst. We find that the IXO only provides $\sim 35\%$ of the ACIS-S3 0.3 – 8.0 keV energy band count rate within a radius of $3'$ from the source. In the 2.0 – 8.0 keV energy band the IXO is more dominant, providing 67% of the ACIS-S3 counts, *but emission from the rest of the galaxy is always significant.*

We estimate that these other point sources, along with the diffuse emission, account for $\sim 80 \pm 30\%$ of the total *ASCA* count rate (the main uncertainty is the uncertainty in the *ASCA* count rate (Yaqoob et al. 1995)). As the IXO, at the luminosity observed in December 2000, would produce $\sim 90\%$ of the total *ASCA* count rate itself, the IXO must have been less luminous in 1993 than it is now. The shape of the hard spectral component in the joint *ROSAT* PSPC and *ASCA* spectral fit was therefore largely determined by the 30 or so other hard X-ray point sources within the central $3'$ of NGC 3628.

It is worth noting that *Chandra* provides *a spectrum that is unambiguously that of the*

IXO alone — the same can not be so easily said for *ASCA* spectra of IXOs, which are typically of a region a few arcminutes in radius. The luminosity of these objects is very similar to that of the rest of the normal spiral or starburst galaxies they inhabit. That contamination of the *ASCA* spectra by unrelated binary and diffuse X-ray emission may be biasing *ASCA* spectral fits in favor of the multi-color disk spectral model is a legitimate concern.

To investigate whether spectral contamination (at the level of $\sim 30\%$ of the hard X-ray counts that we find in NGC 3628) does bias the fitted spectral shape of the hard X-ray emission, we extracted a spectrum of all the emission within a 3 arcminute radius of the IXO (approximately the same region an *ASCA* spectrum would cover). We fit the spectrum with spectral models comprising two absorbed soft thermal components and an absorbed hard component (either a power law or a multi-color disk model), based on the good empirical fit such three component models give to the combined *ROSAT* PSPC and *ASCA* spectra of starbursts (Dahlem, Weaver & Heckman 1998). For the *Chandra* spectrum, two soft thermal components are required to obtain a statistically acceptable fit, but the hard component can equally well be fitted by a multi-color disk or a power law (the difference between the two fits is not significant: $\Delta\chi^2 = 0.7$ for a change by 1 in the number of degrees of freedom). The spectral shape of the fitted hard component (best-fitting $N_{\rm H}$, Γ or kT) was statistically consistent with the spectral fits to the IXO alone, except for a higher model normalization due to the flux from the 33 other X-ray point sources.

This suggests that the reason we do not find the IXO spectrum to be clearly better fit by the multi-color disk model strongly favored by *ASCA* observations of other IXOs (Colbert & Mushotzky (1999); Makishima et al. (2000)) is due to a real spectral difference between this source and the other IXOs, and not due to spectral contamination (at least not spectral contamination at the 30% level). One possibility is that IXOs can change spectral state, from soft states described by the multi-color disk model to harder power law spectral states (see Colbert & Mushotzky (1999) and Kubota et al. (2001)), and that we are observing the NGC 3628 IXO in such a hard spectral state.

5. Source variability

This source displays strong variability on the time scale of months or years (Dahlem et al. 1995). We are now able to improve previous estimates of the X-ray flux of this source over time by making use of the better-determined *Chandra* spectrum, and by making use of *Chandra*'s spatial resolution to correct the *Einstein*, *ROSAT* PSPC and *ASCA* flux measurements for the contribution from the other point sources and diffuse emission.

Within the ~ 17 hour duration of our *Chandra* observation the count rate of the bright source, in either the broad (0.3 – 8.0 keV) or hard energy band (2.0 – 8.0 keV), is statistically consistent with being constant (although this does not exclude genuine variation on the order of $\sim 10\%$ or less).

Fig. 3 presents our best estimate of the absorption-corrected X-ray flux of this object with time, based on these observations, the papers of Dahlem, Heckman & Fabbiano (1995), Fabbiano, Heckman & Keel (1990), Dahlem et al. (1996) & Yaqoob et al. (1995), and the count rate in a 2 ks *Chandra* ACIS-S3 observation taken on 1999 November 3, as part of a *Chandra* GTO program (Ptak 2000, private communication).

We used the power law model that best-fits the Chandra spectrum to predict *Einstein*, *ROSAT* (PSPC & HRI) and *ASCA* count rates. The ratio of the observed to predicted count rate, for any particular observation, multiplied by the absorption corrected X-ray flux (0.3 – 8.0 keV energy band) from this Chandra observation is the estimated X-ray flux plotted in Fig. 3.

For the *Einstein*, *ROSAT* PSPC and *ASCA* observations we have calculated a correction to obtain the flux due to the bright source alone (given the significant flux from other point sources and diffuse emission, see § 4). We estimate that approximately 48% of the *Einstein* count rate, 33% of the *ROSAT* PSPC count rate and 78% of the *ASCA* count rate was due to diffuse X-ray emission and point sources other than the IXO.

The relative fluxes of the IXO during the Einstein ROSAT and ASCA observations differ somewhat from the work of Dahlem et al. (1995) and Dahlem, Weaver & Heckman (1998), due to our correction for emission from other point sources and diffuse gas, and due to the strong dependence of absorption-corrected flux on the assumed spectral shape.

The IXO was substantially brighter in the early 1990s than it is now, with an intrinsic X-ray luminosity (0.3 – 8.0 keV energy band) of $\sim 5 \times 10^{40}\,\mathrm{erg\,s^{-1}}$. This makes it one of the most luminous IXOs, only slightly less luminous than the source in M82 (Kaaret et al. 2001; Makishima et al. 2000). A drop in flux by a factor $\gtrsim 27$ occurred between late 1991 Dec. and 1994 May (Dahlem et al. 1995). Our estimate of a low X-ray flux from the IXO in the 1993 December *ASCA* observation is consistent with this fading, given the non-detection of the source by the *ROSAT* HRI only 5 months later.

One should bear in mind that Fig. 3 is based on the assumption that spectral shape of the source has remained the same, only changing in absolute luminosity. Given the large variations in derived luminosity, it is quite possible that the spectral shape has changed, due to intrinsic changes in the source itself or possibly even variations in foreground absorption (as discussed by Dahlem, Heckman & Fabbiano (1995)).

6. Discussion, speculation and conclusions

What is this X-ray-luminous source? Given the substantial offset of the brightest X-ray source from the nucleus of NGC 3628 ($\sim 20'' \equiv 970$ pc), this object can not be a SMBH inefficiently radiating X-rays, as dynamical friction would make a SMBH fall to the center of the galaxy within an astronomically short time. This object is clearly another example of an IXO (or ULX). Is it a candidate intermediate mass black hole, or can it be explained by models involving X-ray-luminous supernovae or beamed X-ray emission from normal BH binaries?

Interpretations of this source as either a young X-ray luminous SNR or a supernova remnant evolving in a high-density medium (Franco et al. 1993) have problems. Most young SNRs have soft thermal X-ray spectra (Schlegel 1995), unlike the observed *Chandra* spectrum of this object (§ 4). Spectrally this source is consistent with some models of supernovae in high-density environments which predict power-law-like X-ray spectra with photon indices of $\Gamma = 1.6 - 2.0$ (Plewa 1995), as the power law spectral model fit to the Chandra spectrum gives $\Gamma = 1.8 \pm 0.2$. Nevertheless, the pattern of source variability seen (the observed increase in flux after the original peak and strong decline, see § 5), along with an upper limit on the radio flux at this location significantly lower than known radio supernovae (§ 3), are convincing evidence against a supernova-related interpretation.

Although the *ASCA* spectra of most other known IXOs are clearly better fit by a multi-color disk model than a power law model (Colbert & Mushotzky (1999); Makishima et al. (2000)), our *Chandra* spectrum is better fit by a power law than by a multi-color disk model. Three IXOs observed with *ASCA* appear to show changes in spectral state, from a soft state well represented by a multi-color disk to a hard state best modeled as a power law (Colbert & Mushotzky (1999); Kubota et al. (2001)), and it is possible that the NGC 3628 source represents another IXO in such a hard spectral state. Our fitted power law slope, $\Gamma = 1.8 \pm 0.2$, is very similar to that seen in Galactic BH binary candidates in their hard state (see references in Esin et al. (1998)), or to the canonical $\Gamma = 1.7$ power law of AGN. More *Chandra* spectra of IXOs will be necessary to convincingly determine the spectral properties of this class of object.

With an absorption-corrected 0.3 – 8.0 keV X-ray luminosity of $1.1 \times 10^{40}\,\mathrm{erg\,s^{-1}}$ in this observation (assuming the emission to be isotropic), and a peak luminosity of perhaps $\sim 5 \times 10^{40}\,\mathrm{erg\,s^{-1}}$ in the early 1990s, this object is one of the more luminous IXOs known (others of this class more typically have 0.5 – 10 keV luminosities of $10^{39} - 10^{40}\,\mathrm{erg\,s^{-1}}$ (Makishima et al. 2000), while the luminous source in M82 reaches $\sim 10^{41}\,\mathrm{erg\,s^{-1}}$ at maximum). Both of these objects display strong variability, with X-ray luminosities changing by at least an order-of-magnitude over a period of a few years.

This object is not the only IXO in NGC 3628. Another luminous X-ray source $\sim 5'$ to the east of the nucleus (but still within the disk of NGC 3628) was detected in the earlier *ROSAT* and *ASCA* observations (source 14 in Dahlem et al. (1996), see also Yaqoob et al. (1995)). Unfortunately this source lies outside the region covered in these Chandra observations, but should be covered in the recent (currently unpublished) *XMM-Newton* observation of NGC 3628. Based on the relative *ROSAT* PSPC count rates and assuming a similar spectrum for both objects, the second IXO had an absorption-corrected 0.3 – 8.0 keV X-ray luminosity of $1.2 \times 10^{40}\,\mathrm{erg\,s^{-1}}$ in late 1991.

That both M82 and NGC 3628 are also both archetypal starburst galaxies is perhaps a coincidence, but it is interesting to speculate on the possibility of a link between the formation of large numbers of massive stars and the growth of massive black holes from stellar mass remnants (Taniguchi et al. 2000). There is some form of relationship between starbursts and type 2 Seyfert galaxies (Heckman et al. 1989; Terlevich (1990); Terlevich, Diaz & Terlevich (1990); Cid Fernandes & Terlevitch 1995; González Delgado, Heckman & Leitherer 2001; Levenson, Weaver & Heckman 2001a, 2001b), although not necessarily directly evolutionary in kind. If IXOs are intermediate mass black holes, might they be a "missing-link" connecting star formation and black hole formation?

The model of IXOs as relatively normal BH X-ray binaries (or perhaps analogues of the Galactic microquasars) remains a strong contender. As King et al. (2001) argue, the apparently high numbers of IXOs in star-forming galaxies may be a problem for models invoking intermediate mass black holes. In contrast, elevated chances of seeing a beamed (but otherwise normal) X-ray binary are expected in starburst galaxies. The high-amplitude variability seen in both the NGC 3628 and M82 IXOs is also a natural consequence of this model (see King et al. (2001)).

Testing the various hypotheses currently in the literature requires coordinates of IXOs accurate to $\lesssim 1''$, in order to search for counterparts at other wavelengths (e.g. very dense young stellar clusters, or binary companions under the beaming hypothesis) and to study the environments in which these objects are found and may have formed in. This is a job only *Chandra* can perform.

It is clear that *Chandra* has much to offer in the study of these X-ray sources. As we have demonstrated with this study of the IXO in NGC 3628, it is possible to obtain absolute positions accurate to within $0''.5$, and spectra free from contamination by unrelated X-ray point sources and diffuse emission. Both of these capabilities are vital to further the study of these intriguing objects.

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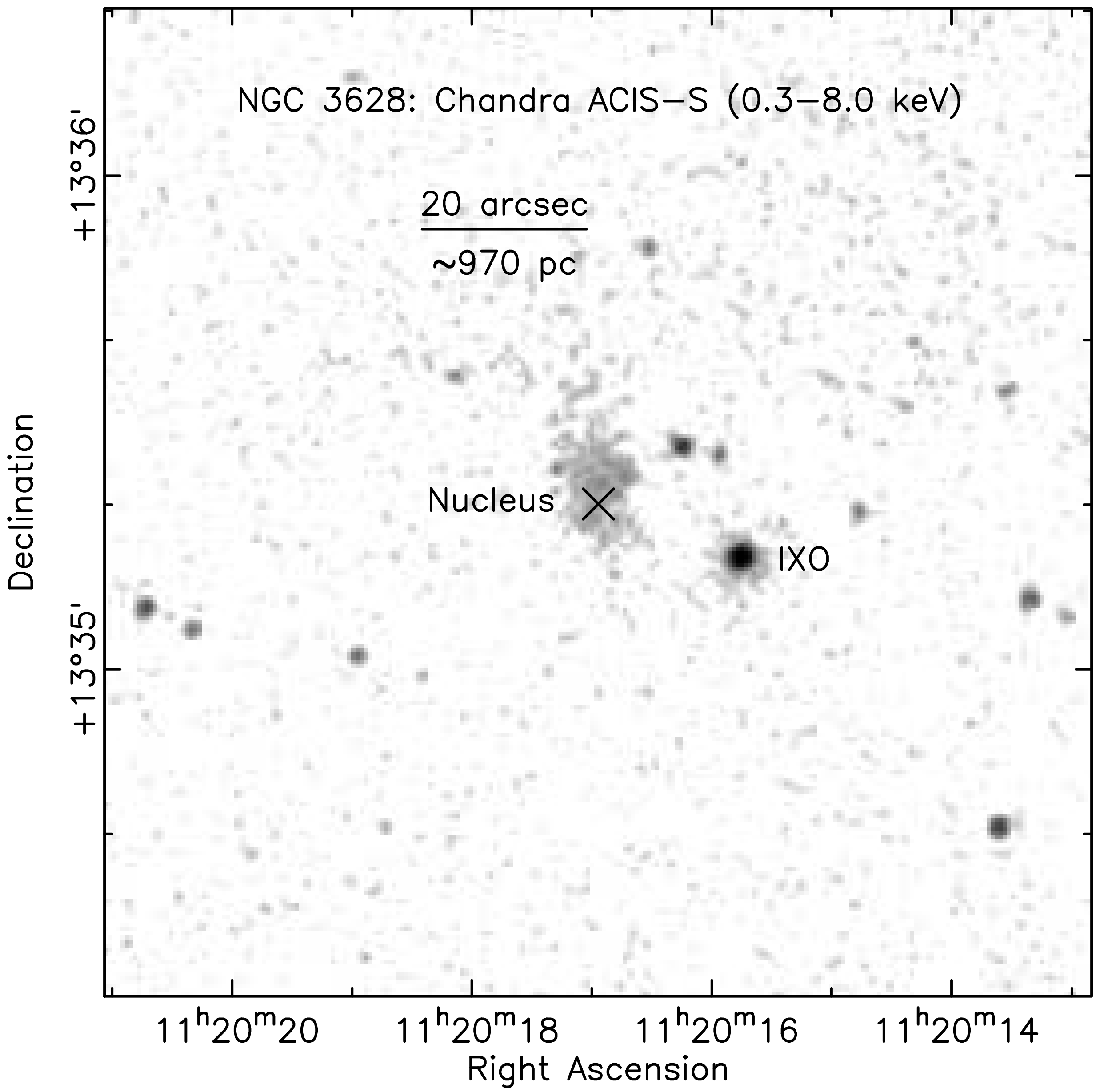

Fig. 1.— *Chandra* ACIS-S3 X-ray image (0.3 – 8.0 keV energy band) of the central 2′ square of NGC 3628. The position of the 365 MHz radio continuum peak, presumed to be the nucleus of the galaxy, is marked by a black cross. The data has been smoothed with a Gaussian mask of FWHM 1″, and is shown on a logarithmic intensity scale covering 3 orders of magnitude in surface brightness from 8×10^{-6} to 8×10^{-3} counts s^{-1} arcsec^{-2}. The *Chandra* data also reveals wide-spread low surface brightness diffuse X-ray emission that covers this entire region at lower surface brightness.

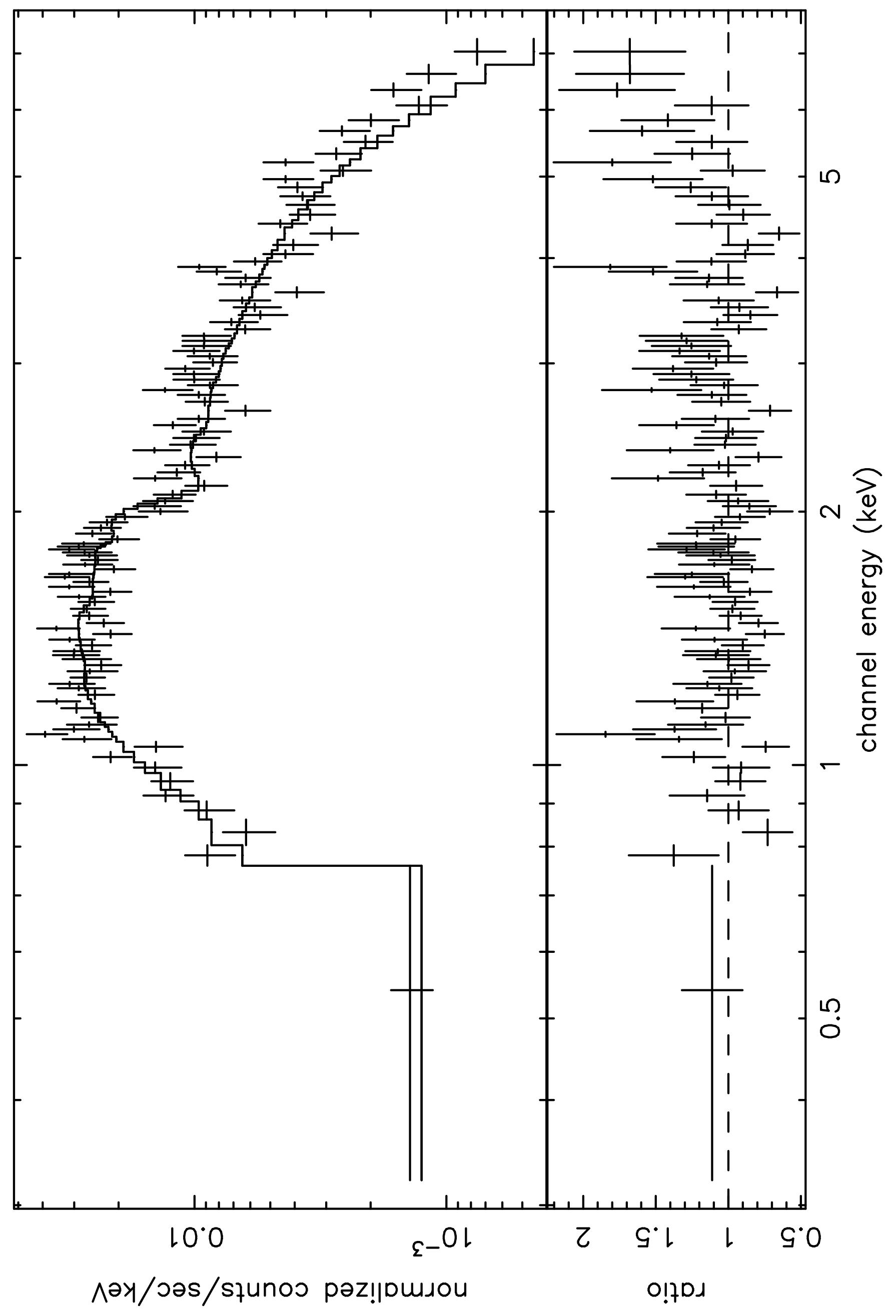

Fig. 2.— Chandra ACIS-S3 spectrum of the IXO. The solid line shows the best-fitting absorbed power law model fit to the data in the energy range 0.3 – 8.0 keV (see § 4 and Table 2). The lower panel shows the ratio of the data to the model.

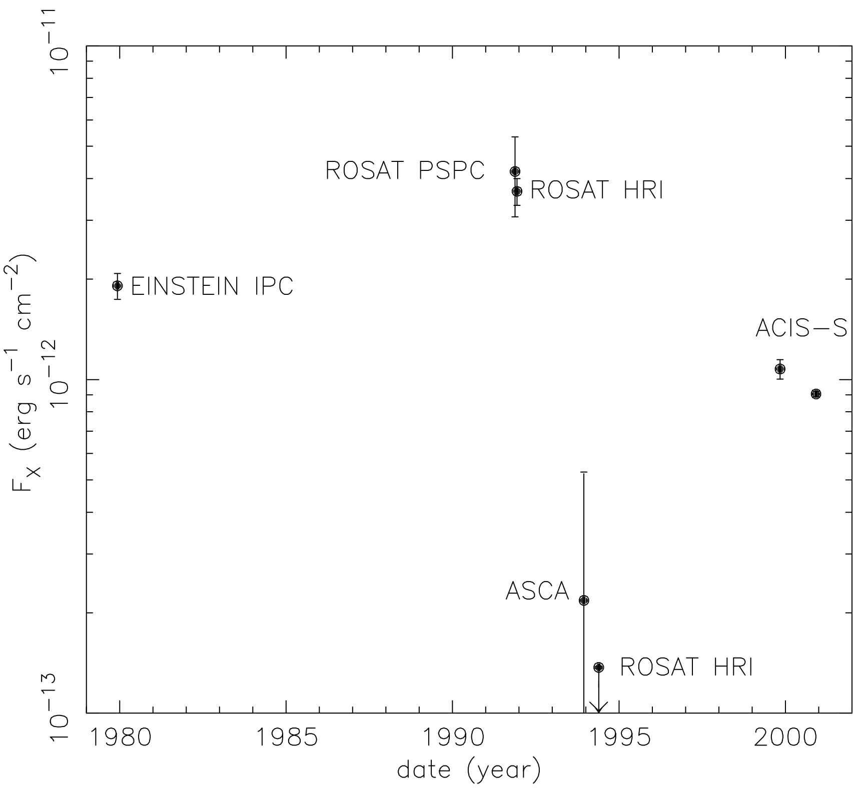

Fig. 3.— Our best estimate of the X-ray flux (in the 0.3 – 8.0 keV energy band) of the NGC 3628 IXO from 1979 Dec. through to 2000 Dec., based on the observed count rates from a variety of X-ray instruments, assuming the *Chandra*-observed spectral shape has remained constant. The lower-spatial resolution *Einstein*, *ROSAT* PSPC and *ASCA* measurements have been corrected to take account of unrelated point source and diffuse X-ray emission falling within the spectral-extraction region. Error bars represent 1σ uncertainties in observed count rates alone.

Table 1. The location of the nucleus of NGC 3628 and the IXO

Observed feature	α (J2000) (h m s)	δ (J2000) ($^\circ$ $'$ $''$)	Reference	Offset[a] $''$
Peak of central HI disk	11 20 17.03	+13 35 19.95	Cole , Mundell & Pedlar (1998)	19.6
Radio recombination line peak	11 20 17.02	+13 35 19.85	Zhao et al. (1997)	19.4
CO molecular disk	11 20 17.00	+13 35 19.85	Irwin & Sofue (1996)	19.2
K-band nucleus	11 20 17.00	+13 35 22.60	Unpublished imaging by Colbert	20.3
365 Mhz peak	11 20 16.95	+13 35 20.10	Douglas et al. (1996)	18.6
Large-scale HI kinematic center	11 20 16.46	+13 35 29.60	Wilding, Alexander & Green (1993)	18.9
Secondary peak in CO emission	11 20 15.96	+13 35 20.90	Irwin & Sofue (1996)	7.9
IXO (CXOU J112015.8+133514)	11 20 15.75	+13 35 13.60	This work	···

[a]Angular distance from this position to the IXO in arcseconds.

Table 2. Best-fitting spectral models for the IXO Chandra spectrum

XSPEC model[a]	$N_{\rm H}$[b]	Γ[c]	Norm.[d]	kT[e]	Norm.[f]	$EW_{\rm Fe-K}$[g]	σ[h]	χ^2_ν	χ^2 (ν)[i]
Statistically acceptable fits with well-constrained model parameters									
wabs*pow	$7.5^{+1.1}_{-0.8}$	$1.69^{+0.15}_{-0.14}$	$1.44^{+0.33}_{-0.25}$	...	...	...	...	1.03	111.4 (108)
wabs*pow[j]	$8.0^{+1.2}_{-1.1}$	$1.82^{+0.21}_{-0.20}$	$1.63^{+0.41}_{-0.32}$	...	...	...	...	**0.97**	**93.9 (97)**
wabs*(pow+gauss)	$7.6^{+1.2}_{-1.1}$	$1.71^{+0.19}_{-0.19}$	$1.47^{+0.38}_{-0.29}$	...	...	$0.16^{+0.27}_{-0.16}$	0.01 (f)	1.01	108.3 (107)
wabs*bremms[j]	$7.1^{+1.0}_{-0.8}$	...	...	$5.9^{+3.5}_{-1.7}$	$1.74^{+0.26}_{-0.19}$	...	...	0.96	93.1 (97)
wabs*diskbb[j]	$5.8^{+0.8}_{-0.7}$	...	...	$1.38^{+0.20}_{-0.17}$	$8.67^{+5.40}_{-3.48}$	...	...	1.01	97.7 (97)
Statistically unacceptable fits, or models with poorly constrained physical parameters									
wabs*brems	$6.6^{+0.9}_{-0.6}$	...	...	$9.4^{+5.8}_{-2.7}$	$1.62^{+0.17}_{-0.11}$	...	...	1.09	117.8 (108)
wabs*mekal	$6.4^{+0.7}_{-0.6}$	...	...	$10.3^{+5.7}_{-2.6}$	$4.33^{+0.27}_{-0.26}$	...	...	1.14	123.1 (108)
wabs*mekal[j]	$6.8^{+0.8}_{-0.7}$	...	...	$7.1^{+3.6}_{-1.7}$	$4.36^{+0.34}_{-0.30}$	...	...	1.07	104.2 (97)
wabs*diskbb	$5.2^{+0.7}_{-0.5}$	...	...	$1.71^{+0.26}_{-0.21}$	$4.05^{+2.44}_{-1.61}$	...	...	1.35	146.3 (108)
wabs*(pow+gauss)	$8.0^{+2.0}_{-1.3}$	$1.83^{+0.35}_{-0.25}$	$1.64^{+0.86}_{-0.39}$	...	...	$1.3^{+14.3}_{-1.3}$	$0.9^{+19.1}_{-0.9}$	0.96	102.1 (106)
wabs*(diskbb+gauss)	$5.3^{+0.8}_{-0.7}$	...	...	$1.66^{+0.29}_{-0.22}$	$4.43^{+3.05}_{-1.90}$	$0.37^{+0.39}_{-0.37}$	0.01 (f)	1.30	139.3 (107)
wabs*(diskbb+gauss)	$6.1^{+1.6}_{-1.0}$	...	...	$1.19^{+0.35}_{-0.49}$	$14.3^{+78.2}_{-8.7}$	$12.5^{+116.8}_{-7.8}$	$1.45^{+18.55}_{-0.78}$	0.96	101.8 (106)
wabs*(diskbb+pow)	$6.3^{+2.5}_{-1.1}$	$-0.7^{+3.7}_{-2.3}$	$0.02^{+1.46}_{-0.02}$	$0.99^{+0.46}_{-0.99}$	$26.0^{+806.6}_{-19.2}$	...	...	0.96	102.1 (106)

[a]Model specification within XSPEC. Model components used were *wabs* (foreground X-ray absorption), *pow* (power law model), *gauss* (a Gaussian line), *diskbb* (multi-color disk model), *brems* (thermal bremsstrahlung) & *mekal* (MEKAL hot plasma model with Solar element abundances).

[b]Hydrogen column, in units of 10^{21} cm^{-2} .

[c]Power law model photon index.

[d]Power law model normalization, in units of 10^{-4} photons keV^{-1} cm^{-2} s^{-1} at 1 keV.

[e]Characteristic temperature in keV. For the multi-color disk model this is temperature at the inner disk radius, for the bremsstrahlung and hot plasma models this is the gas temperature.

[f]Model normalization. For the multi-color disk model this is in units of $10^{-3}(R_{\rm in}/D_{\rm 10kpc})^2 \cos\theta$, where $R_{\rm in}$ is the inner radius of the disk in km, $D_{\rm 10kpc}$ is the distance to the source in units of 10 kpc, and θ the inclination of the disk with respect to the line of sight. For the bremsstrahlung and hot plasma models the normalization is in units of $10^{-4}K$. For the thermal bremsstrahlung model $K = 3.02 \times 10^{-15} \int n_{\rm e} n_{\rm i} dV/4\pi D^2$, where $n_{\rm e}$ and $n_{\rm i}$ are the electron and ion number densities in units of cm^{-3}, dV a volume element and D the distance to the source in cm. For the MEKAL hot plasma model, $K = 10^{-14} \int n_{\rm e} n_{\rm H} dV/4\pi D^2$, where $n_{\rm H}$ is the proton number density in units of cm^{-3}.

[g]Equivalent width of the the Gaussian line component, with a fixed central energy of 6.4 keV.

[h]Width (1σ) of the 6.4 keV Gaussian line feature in keV.

[i]Fit χ^2 and number of degrees of freedom (ν).

[j]Fits using only the data in the energy band 0.3 – 5.0 keV.

Note. — Unless otherwise noted all fits are to data in the 0.3 – 8.0 keV energy band. All errors quoted are 90% confidence for a number of interesting parameters equal to the number of free parameters in the fit. Parameters fixed during fitting are denoted by (f). Our preferred spectral model (an absorbed power law) has been highlighted in bold face type.

Table 3. IXO count rates and X-ray fluxes

Energy[a]	Rate[b]	F_X[c]	L_X[d]
0.3 – 8.0	5.36 ± 0.10	9.40	1.1×10^{40}
0.3 – 2.0	2.83 ± 0.07	4.75	5.7×10^{39}
2.0 – 8.0	2.53 ± 0.07	4.65	5.6×10^{39}

[a]Energy range in keV.

[b]Background-subtracted ACIS-S3 count rate, in units of 10^{-2} count s^{-1}.

[c]Absorption-corrected (*i.e.* intrinsic) X-ray flux, based on the best-fitting absorbed power law model (fit only within the 0.3 – 5.0 keV energy range), in units of 10^{-13} erg s^{-1} cm^{-2}. Derived fluxes depend on which spectral model is used, and vary from these values by up to $^{+10}_{-30}$% if other spectral models from Table 2 are used.

[d]Absorption corrected X-ray luminosity in units of erg s^{-1}, assuming D = 10 Mpc.